Mineralogy and Petrogenesis of the Lake Zone, Thor Lake rare metals deposit, NWT., Canada

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ABSTRACT

The Proterozoic (ca. 2.1 Ga) Blatchford Lake complex hosts significant concentrations of rare-metals at the core of a peralkaline granite-syenite pluton. After emplacement of the Grace Lake granite and the Thor Lake syenite within it, a body of nepheline syenite, ijolite and urtite was intruded beneath the present-day Lake zone. This is the largest of five zones of mineralisation and lies close to the apex of the Thor Lake syenite, a region which was then subjected to albitisation, microclinisation and, finally, rare-metal mineralisation. The underlying silica-undersaturated rocks contain clots of rare-metal bearing minerals, including cerianite-(Ce), britholite-(Ce), thorite and Ca-catapleiite, interstitial to nepheline and aegirine. The Lake zone itself contains major quantities of Zr (in zircon), Nb (in ferrocolumbite, pyrocholore group minerals, aeschynite group minerals and fergusonite-(Y)) and Ce (in allanite-(Ce), monazite-(Ce) and bästnasite group minerals). Lesser amounts of Ta, Y, HREEs, U, Th and Ga are also present, mainly as minor components of rare-metal-bearing minerals. Electron microprobe analyses of the major rare-metal-bearing minerals are presented.

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INTRODUCTION

The Aphebian Blatchford Lake intrusive complex lies approximately 100 km southeast of Yellowknife, N.W.T. and 5 km north of the Hearne Channel, Great Slave Lake (Fig. 1). It can be divided into two portions: a western, less alkaline series of gabbros, anorthosites, granites and syenites and an eastern peralkaline granite-syenite and silica-undersaturated system (Davidson, 1982). The western rocks have been subdivided into: the Hearne Channel and Mad Lake granites, the Whiteman Lake quartz syenite and the Caribou Lake gabbro-diorite. These rock bodies all show alkaline to subalkaline characteristics in contrast to the eastern-lying Grace Lake granite and Thor Lake syenite (Fig. 2) which have peralkaline affinities. Typically, the hypersolvus peralkaline granite contains abundant perthite, quartz and riebeckite with accessory fluorite, zircon, apatite and monazite. The contact relationship between granite and syenite is fairly clear and is generally marked by an abrupt change in lithology from the outer granite to the inner syenite. This sharp boundary is followed by a rim-shaped, fayalite-bearing syenite which was emplaced into the surrounding Grace Lake granite and was succeeded by the gradual inward crystallisation of the Thor Lake syenite. Air photo interpretations have shown that many circular ring-shaped fractures pervade the complex, providing evidence for emplacement of a magma body characteristic of a geometrically-simple, anorogenic ring complex.

A substantial body of nepheline syenite, found recently immediately beneath the Lake zone deposit by drilling (Fig. 3), is an important part of the Blatchford Lake intrusive complex. Compositionally, this subsolvus body varies from nepheline syenite to nepheline monzosyenite (IUGS classification) but in some cases the nepheline and pyroxene contents are high enough for the term ijolite or feldspathic ijolite to be appropriate (LeBas, 1977). Other rock types include pectolite syenite, and sodalite syenite (urtite), nepheline syenite (as sills or

dykes) and pegmatitic pods with aegirine and nepheline crystals up to 10 cm in size. Accessory minerals within these rocks include: andradite, zircon, allanite-(Ce), pectolite, zeolites, fluorite, sodalite, hydrohetaerolite, Ca,Zr-silicates, Nb,Ti-silicates, La-silicates and britholite group minerals.

The Blatchford Lake complex shows numerous features in common with some of the better known alkaline rock provinces in the world including the Sn granites of Nigeria, the felsic plutonic rocks of the Arabian Shield and various alkaline rocks of the Lovozero Massif, U.S.S.R. Numerous workers including Badham (1978), Hoffman (1980, 1981, 1987), Bowring *et al.* (1984), Davidson (1978, 1981, 1982) and most recently Trueman *et al.* (1988) have contributed to our understanding of the petrology, mineralogy and geochemistry of the area.

THOR LAKE RARE-METAL DEPOSIT

Within the Thor Lake syenite is a body of Be, Nb, REE, Y and Zr mineralisation. Five distinct zones have been recognised: the R, S, T, Lake and Fluorite zones (Fig. 2). Of these, the two most economically important are the T-zone (Be, Nb and Ce) and the Lake zone (Nb, Ce, Y and Zr). Exploration has been underway since 1970, first for U and Th, then for Nb and Ta and finally for Be, Y and rare earths. The rare-metal potential, particularly that of Be, has been studied extensively by Highwood Resources Ltd. and the Hecla Mining Co.

The T zone is the most studied and probably best understood. de St. Jorre (1986) identified a number of unusual rare-metal-bearing minerals, including the beryllium minerals phenakite, bertrandite and members of the gadolinite and helvite groups. Other minerals of potential economic importance that were identified include members of the bastnäsite group, thorite, ferrocolumbite and zircon. The Lake zone has by far the greatest potential for Nb, Zr, Y and REEs although, mineralogically, it is less complex than the T zone. Approximately 85-

90 mineral species have now been identified in the Thor Lake deposit (Table 1); many more may be present.

GEOLOGY OF THE LAKE ZONE

In areal extent, the Lake zone is easily the largest of the five zones of mineralisation, and covers an approximately triangular area of 1.8 square km. Because of its altered nature, it is recessive and flat lying with less than 5% outcrop.

In general, the Lake zone contains altered and brecciated syenite which has been affected by late-stage magmatic to post-magmatic alteration. At present, two broad subdivisions can be made: an outer Wall zone composed essentially of quartz and feldspar surrounds an inner Core zone which is biotite-rich and hosts most of the mineralisation. In general, the Wall zone contains abundant microcline, albite and quartz along with minor biotite, magnetite, hematite, calcite, fluorite, pyrite, chalcopyrite, sphalerite, galena, monazite-(Ce) and ferrocolumbite. Early phases of K- and then Na-metasomatism resulted in a felsic rock which, in many places, is mono- or dimineralic. Magnetite and hematite, either in the form of large, discrete grains or as fine-grained crystals dusting feldspar, are the dominant oxides. Late-stage biotite, calcite, fluorite plus minor monazite-(Ce) and ferrocolumbite are present although uncommon.

The Core zone exhibits the same types of alteration sequences but, in addition, shows continued post-magmatic change in the form of extensive biotite flooding, Fe enrichment and significantly greater quantities of rare metals. Large-scale quartz flooding within this zone is considered to result from fenitisation by the underlying nepheline syenite. Accessory minerals include those seen in the Wall zone plus arfvedsonite, apatite, ankerite, cassiterite and

ilmenite. Table 2 presents a generalised paragenetic sequence for both the Wall and Core zones.

It is possible that retrograde boiling of the more fluid-rich (H_2O, CO_2, F, Cl) magma further concentrated dissolved Na and K, as well as Zr, REEs, Nb, Y and other incompatible elements. Best (1982) noted that mineralogical changes such as microclinisation and albitisation are promoted by retrograde boiling. In essence, then, the Lake zone may be the result of late-stage to post-magmatic alteration, as witnessed by albitisation, microclinisation and associated rare-metal enrichment. This type of alteration is frequently associated with late-stage plutons of highly fractionated granitoid suites (Pollard, 1986). Zonation from early K and Na metasomatism to later Fe metasomatism, greisenisation and silicification is common. In the Lake zone, as it is preserved today, alteration did not progress as far as in the T zone, hence the lack of greisenisation.

RARE METAL MINERALOGY

A detailed account of the mineralogy of the Lake zone rocks will appear elsewhere. The purpose here is to identify the principal host minerals for rare metals and, where possible, to draw inferences concerning the nature of the mineralising processes.

Zr Mineralisation

Zircon, by far the most important Zr-bearing mineral, appears at least three times in the paragenetic sequence (Table 3): An early, euhedral, strongly zoned type (1); a later, subhedral type (2); and a minor, anhedral, late-formed intergrowth with samarskite-(Y)-type (3). Many of the zircons deviate substantially from the ideal formula [$ZrSiO_4$] and are probably H_2O-bearing, as may be seen from Table 4. Hf/(Hf+Zr) ratios are typically low. The REE maximum is

generally found at Nd but it can vary from Sm to Dy (even atomic numbers only). Metamictisation is ubiquitous and dating of this body using zircon should be carried out with extreme caution.

Nb Mineralisation

A wide range of Nb-minerals has been produced, including those listed in Table 1. However, quantitatively, ferrocolumbite is by far the most important. It occurs twice in the paragenetic sequence with the earlier appearance being in the form of "pinwheel" clusters (Fig. 4). Later ferrocolumbite occurs as larger bladed crystals and also intergrown with magnetite, uranpyrochlore and allanite-(Ce). Table 4 shows a typical ferrocolumbite analysis. It can be seen that the Nb/(Nb+Ta) ratio is high (0.991) - a value that is much larger than those for both chondites and MORB. This is a feature common to all Nb-bearing minerals at Thor Lake.

Other important Nb-bearing minerals in the Lake zone belong to the pyrochlore group. To date, pyrochlore [(Ca,Na)2Nb2O6(OH,F)], ceriopyrochlore [(U,Ca,Ce)2(Nb,Ta)2O6(OH,F)], uranpyrochlore [(U,Ca,Ce)2(Nb,Ta)2O6(OH,F)] and betafite [Ca,Na,U)2(Ti,Nb)2O6(OH,F)] have been positively identified. They are usually found associated with zircon, monazite-(Ce) and ferrocolumbite in quartz- and albite-rich rocks. Table 4 shows typical compositions. Aeschynites form the remaining mineral group of importance. Three members have been found in Lake zone rocks: aeschynite-(Nd) [(Nd,Ce,Ca)(Ti,Nb)2(O,OH)6], nioboaeschynite-(Nd) [(Nd,Ce,Ca)(Nb,Ti)2(O,OH)6] and nioboaeschynite-(Ce) [(Ce,Nd,Ca)(Nb,Ti)2(O,OH)6]. These all occur as anhedral grains closely associated with fergusonite-(Y) or zircon. All grains were found to be non-metamict and hence, not surprisingly, have low U and Th values (Table 4).

Y and REE Mineralisation

Zircon and fergusonite-(Y) - ideally $YNbO_4$ (Fig. 5), form the major hosts for Y in Lake Zone rocks, with xenotime [YPO_4] a minor contributor. The fergusonite-(Y) is associated with the subhedral to anhedral "type 2" zircons. It is also found with aeschynite group minerals. Apart from the suite of REEs, fergusonite is chemically simple with only low levels of other elements (Table 4). The compositionally similar mineral samarskite-(Y), which shows some Ca, Fe and Si substitution, may also occur.

Several important Ce-bearing minerals have been recognised in Lake Zone samples, including allanite-(Ce), monazite-(Ce) and members of the bastnäsite group. Like the zircons, the REE-bearing phases occur as early, well-formed crystals and as a later generation of xenomorphic crystals associated with "type 2" zircon. Allanite-(Ce) (Table 4), a REE-rich member of the epidote group, is typically found elsewhere in low temperature metamorphic and hydrothermal vein deposits that are REE-enriched. In the Lake zone rocks, early-formed tabular grains reach 5-6 mm in size, whereas late-formed grains are commonly intimately associated with "type 2" zircons. The allanite-(Ce) often shows dueteric alteration to bastnäsite-(Ce). However, the latter mineral also occurs as blocky, hexagonal crystals. These are either homogeneous or are polycrystals showing contemperaneous growth of parisite. A third, more Ca-rich member of the bastnäsite group, synchysite-(Ce), has been tentatively identified. It replaces allanite-(Ce) along cracks and cleavage planes. Monazite-(Ce) (Table 4) occurs in association with zircon and fergusonite-(Y) and sometimes as blebs or stringers in fluorite.

MINERALOGY OF THE SILICA-UNDERSATURATED ROCKS

The nepheline syenite beneath the Lake zone includes abundant tan-coloured, irregular patches which contain, amongst other minerals, andradite, zircon, manganoan allanite-(Ce), willemite, fluorite, sodalite, analcime, calcite and manganoan pectolite. The presence of this material implies a low temperature of formation, abundant incompatible elements in the melt, high oxygen fugacities and diverse low-temperature metasomatic reactions.

The dominant minerals within these patches are andradite, manganoan allanite-(Ce) and zircon in a matrix of either sodalite (Fig. 6) or immiscible blebs of fluorite in calcite. Andradite is commonly replaced by the manganoan allanite-(Ce) and displays either anomalous first order birefringence or sector zoning.

Other patches contain a bizarre assortment of rare-metal-bearing minerals such as britholite-(Ce), cerianite-(Ce), unidentified La- or Ce-silicates and oxides, hydrohetaerolite, thorite and Ca-catapleiite. Commonly, britholite-(Ce) is found as well-formed, severely metamict, hexagonal grains associated with recrystallised thorite. Cerianite-(Ce) crystals are embedded in a fluorite matrix as small (5-10 μm), euhedral grains, generally associated with anhedral Ca-catapleiite.

DISCUSSION

The Blatchford Lake intrusive suite displays features similar to those of alkaline ring complexes in Nigeria, Saudi Arabia, the U.S.S.R., Greenland and elsewhere (Black *et al.*, 1985; Bowden, 1985). These complexes are petrologically variable but are characterized by the common development of a peralkaline fluid phase and by shallow-level or subvolcanic emplacement which usually involves the

formation of ring dykes or cone sheets. Many of these alkaline ring complexes are enriched in Zr, Nb, Y, Th, U and REEs.

The A-type granites of the Nigerian Shield contain, in addition to significant Sn mineralisation, high levels of F, Nb, Zr, REEs and Y (Bowden, 1985). The style of intrusion and mineralisation in these silica-saturated to oversaturated rocks shows some similarity to the Blatchford Lake complex. As discussed by Bowden *et al.* (1987), there exists in many individual complexes (*e.g.*, Air massif, Niger) an association of outer, marginal leucogabbros and anorthosites with an inner core of granite, syenite and syenite breccia. Also, the structural styles are similar and include the emplacement of simple plutons of circular or eliptical cross-section and ring dykes or cone sheets. Furthermore, there are comparable types of post-magmatic alteration and subsolidus processes in which sodic and potassic metasomatism is followed by acid metasomatism (greisenisation). This may be initiated and driven by the underlying intrusions and may involve scavenging from the local country rock. Mineralisation sequences are also similar but Sn and sulphide minerals dominate over niobates and rare earth-bearing minerals in the Nigerian granites. As in Nigeria, Arabian Shield granites have mineralisation resulting from late-stage hydrothermal alteration through albitisation, microclinisation and greisenisation (Ramsay, 1986; Drysdall and Douch, 1986; and Bokhari *et al.*, 1986). The Velasco Alkaline Province of eastern Bolivia (Fletcher and Litherland, 1981; Fletcher *et al.*, 1981) consists of an early volcanic suite, some 14 interfering circular or elliptical plutons and a late-stage carbonatite. It also exhibits petrological and mineralisation features which are remarkably similiar to those of the Blatchford Lake complex.

Evidence from recent gravity surveys (Birkett *et al.* 1989), indicates that the Blatchford Lake complex is a tabular body composed of a series of subcircular, intrusive lobes. This contrasts with the 'bell-jar' pluton model (Pitcher, 1978;

Roobol and White, 1986) envisaged for the granites of the Nigerian Shield. At Thor Lake, after emplacement of the lobe now represented by the simple, circular-shaped GLG into surrounding Archean granitoids (Fig. 7), syenitic magma forced its way into one of the many cooling-induced ring fractures within the GLG, eventually causing ring-fracture stoping. Influxes of several somewhat different syenite magma pulses would account for the various TLS rock types mentioned earlier. As Davidson (1978, 1981) suggested, the rare metal deposits at Thor Lake may be due to the build-up of incompatible elements in residual fluids. These rare element-rich fluids were generally excluded from the earlier crystallising Grace Lake granite (GLG) and Thor Lake syenite (TLS) but were deposited in the R,S,T, Lake and Fluorite zones. Retrograde boiling may have been responsible for extensive brecciation seen in the Lake zone.

The late-stage volatile and incompatible element enrichment within the TLS promoted many late-stage, subsolidus mineral reactions including albitisation, microclinisation and greisenisation. Such processes have been discussed by Vlasov (1966a,b) and, more recently, by Pollard (1986). Generally, microclinites and albitites are developed at the upper levels of the host rock (*e.g.*, Wall zone). If the conditions are right, greisenisation may ensue (*e.g.*, the T zone). At this point, first stage or type 1 rare-metal-bearing minerals formed. Overall, their relatively low concentrations and moderately well-developed crystal habits seem to suggest an initial accumulation of rare-metals in this 'cap zone' of the TLS.

During these changes, the silica-undersaturated rocks were being emplaced directly beneath the TLS. The hypothesis may then be developed further to include a contribution made by these silica-undersaturated rocks as an extended source for K and Na metasomatism and rare-metal enrichment in the Lake zone. Significant silica remobilisation (with a 30-60 m zone of quartz depletion) occurred immediately above the nepheline syenite, with redeposition of the silica in the

overlying albitites and microclinites. The phenomenon of quartz depletion and redeposition at some distance from the intruding rock body is common in fenite zones (Saether, 1957). A consanguineous rare-metal enrichment feature was probably responsible for the "type 2" or second-stage minerals. These minerals are rather poorly developed, fine-grained and generally occur in the previously mentioned 10-20 m thick bands of mafic rock found deep within the Lake zone. Rare-metal enrichment due to the underlying nepheline syenite may be related to the frequent tan-coloured patches of volatile- and incompatible-element-rich minerals now found within the undersaturated rocks. These occurrences and the mineral reactions peculiar to them, suggest the low temperature metasomatic conditions necessary for the observed enrichment in the overlying rocks.

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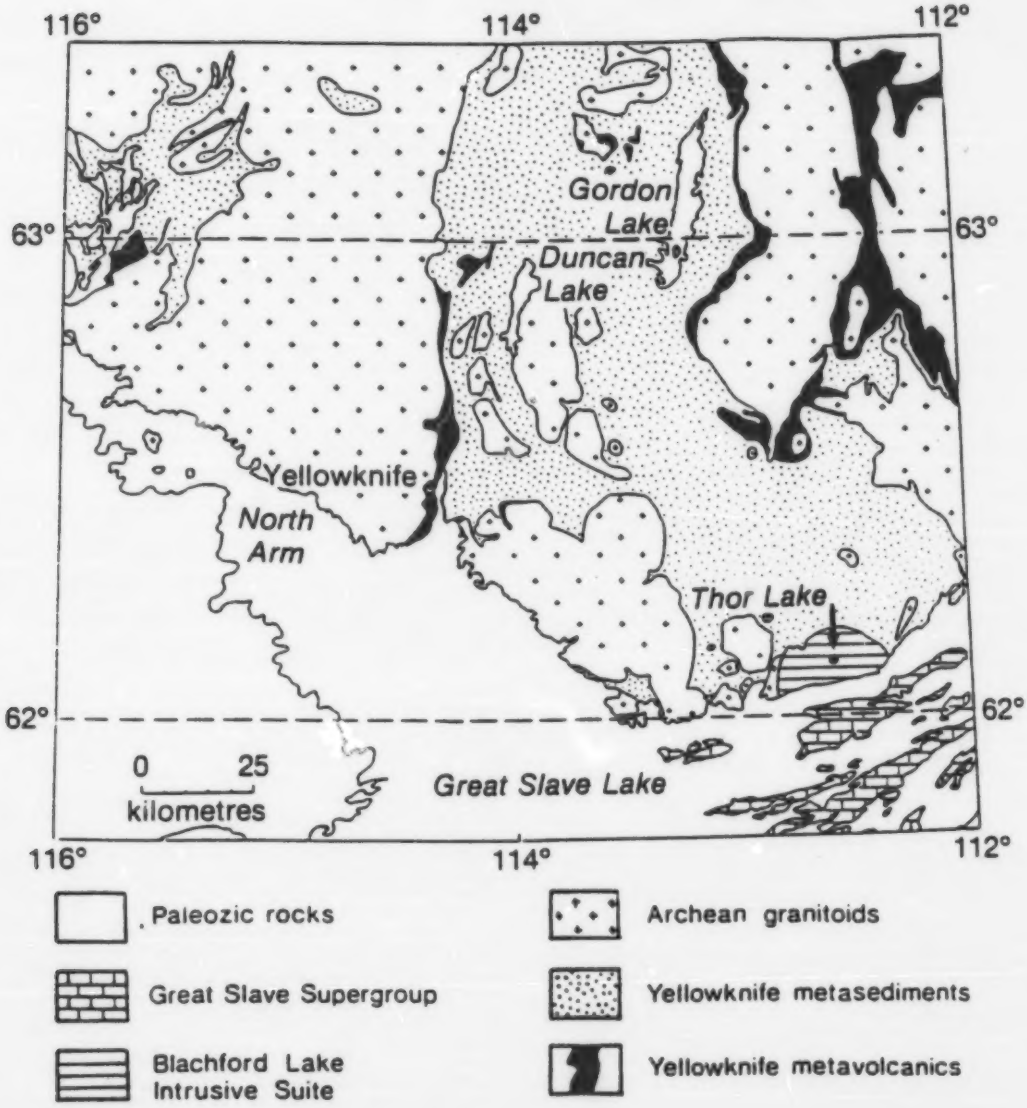


Figure 1: Generalised geological map of the southern Slave Province. Modified after Henderson (1985).

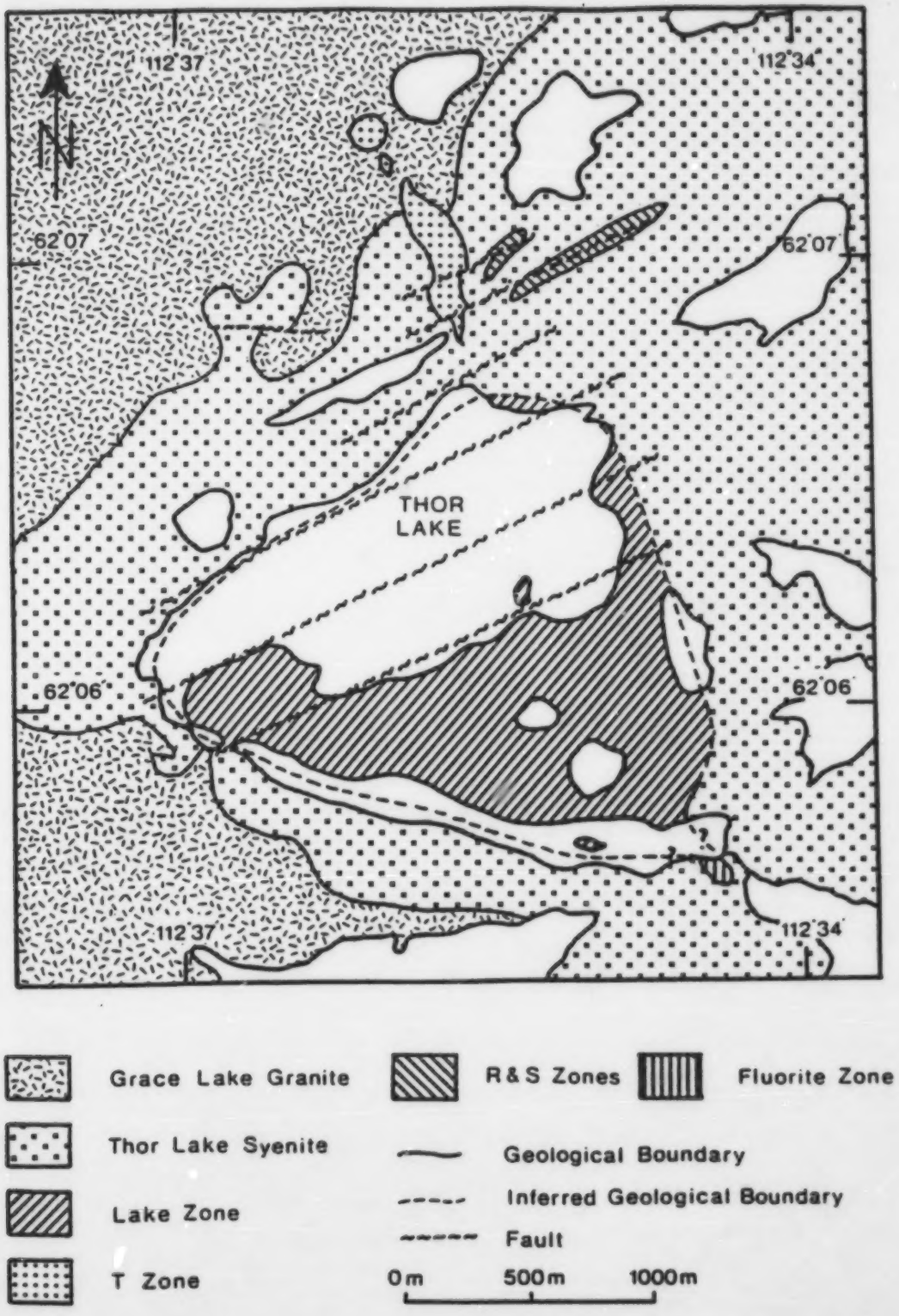


Figure 2: Geological map of the Thor Lake area. After Cerny and Trueman (1985).

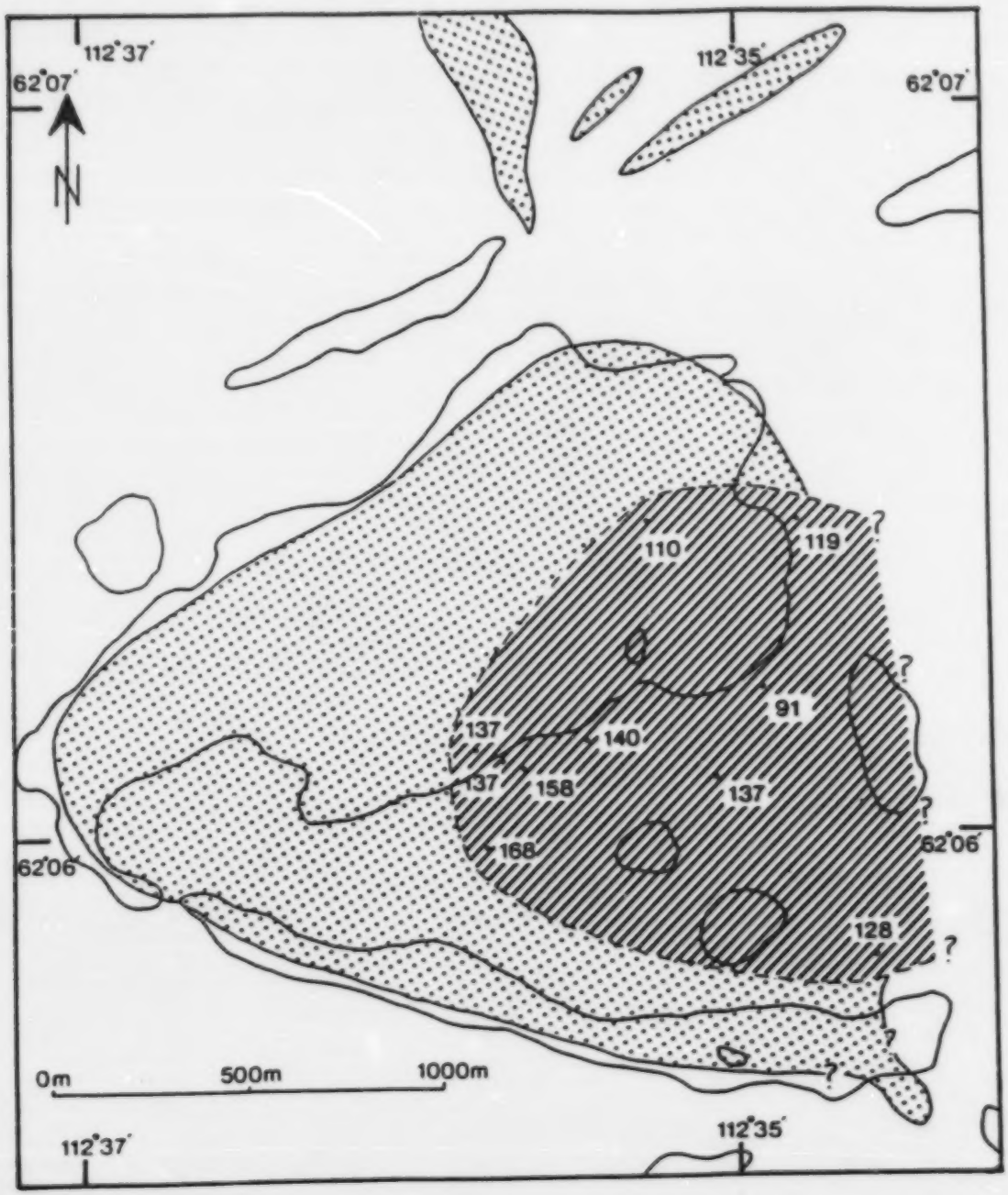


Figure 3: Spatial relationship between zones of mineralisation and silica-undersaturated rocks.

Figure 4: Photomicrograph displaying 'pinwheel' aggregates of ferrocolumbite (FC) in a matrix of fluorite (F). Note the bipyramidal zircons (ZR).

Figure 5: Secondary electron image of anhedral fergusonite-(Y) (FG) and zircon (ZR). Flakes of biotite (BT) are enclosed in the fergusonite-(Y).

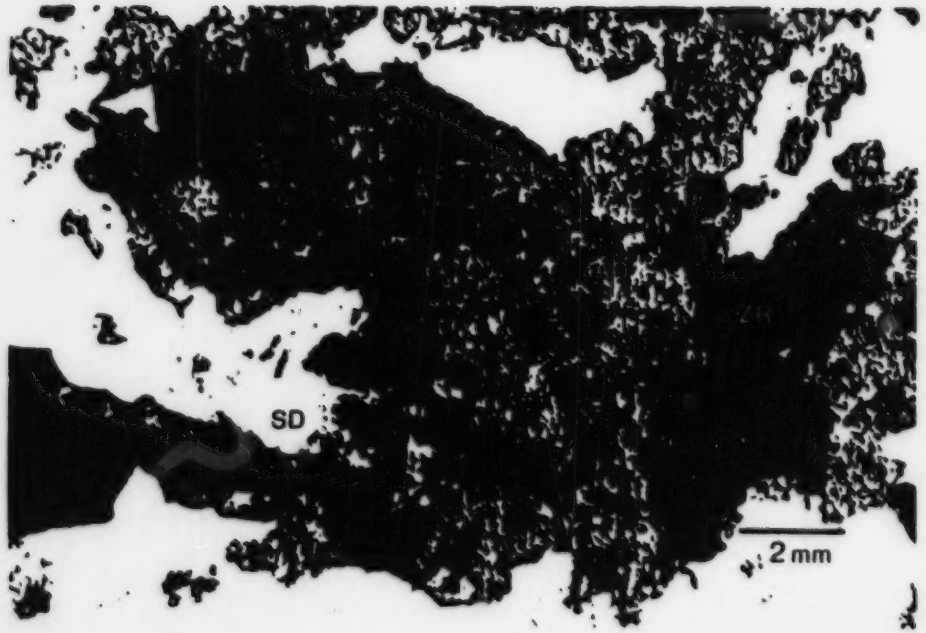


Figure 6: Photomicrograph of andradite (AD) replacing manganoan allanite-(Ce) (A) in a matrix of sodalite (SD). Note the zonally metamict zircon (ZR) in the upper left.

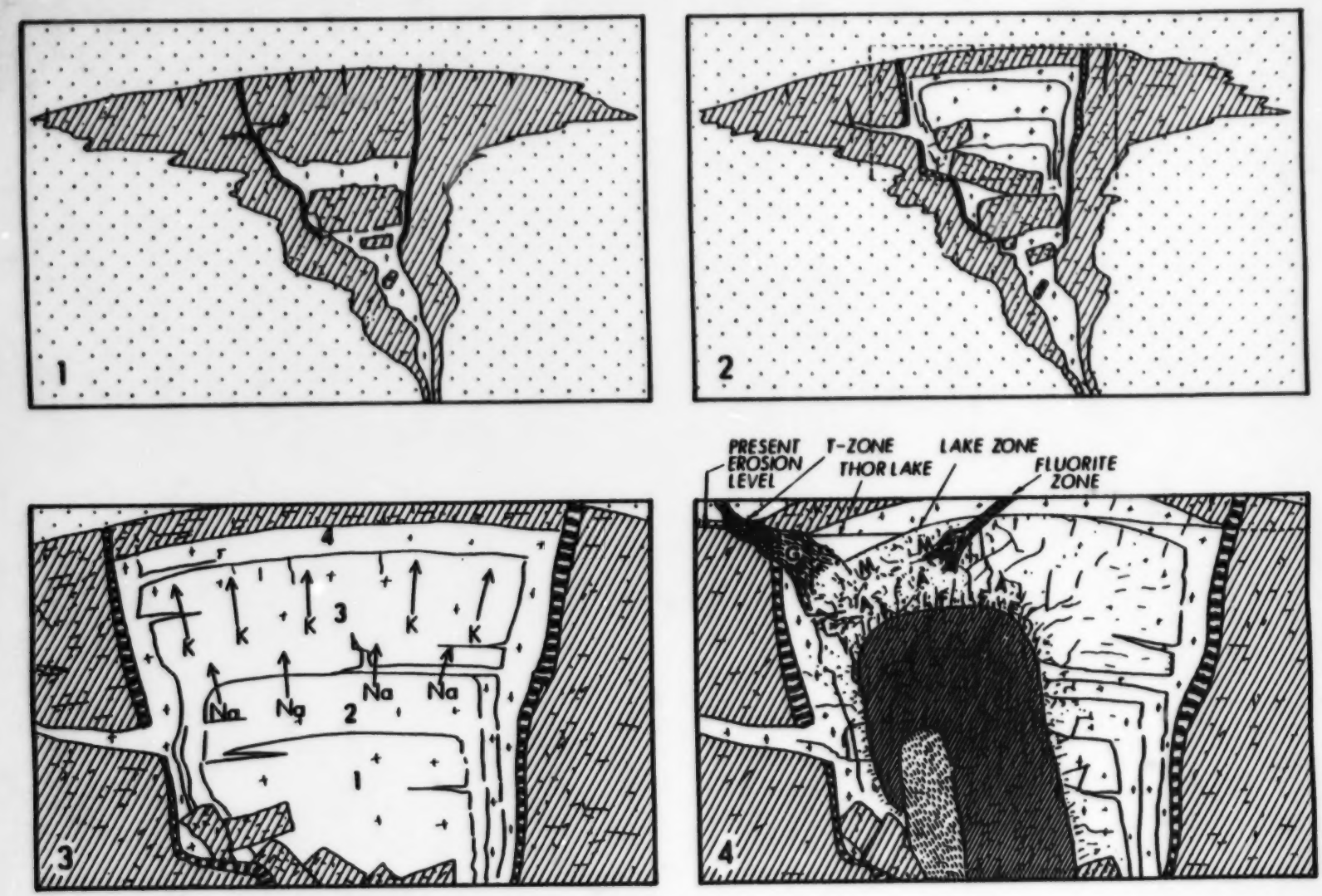


Figure 7: Schematic diagram showing possible stages in the development of the Thor Lake syenite and associated rare-metal deposits. Direction of section is approximately NW-SE. There is some exaggeration in vertical scale for clarity. Area outlined by dashes in 2 is shown enlarged in 3 and 4.

TABLE 1

LIST OF ALL KNOWN MINERAL SPECIES IN THE THOR LAKE RARE-METAL DEPOSITS AND HOST PERALKALINE GRANITE-SYENITE

SILICATES

NAME	FORMULA*
aegirine	$NaFe^{3+}Si_2O_6$
aenigmatite	$Na_2Fe_5^{2+}TiSi_6O_{20}$
albite	$NaAlSi_3O_8$
allanite-(Ce)	$(Ce,Ca)_2(Al,Fe^{3+})_3(SiO_4)_3(OH)$
analcime	$NaAlSi_2O_6:H_2O$
andradite	$Ca_3Fe_2^{3+}(SiO_4)_3$
annite	$KFe_3^{2+}AlSi_3O_{10}(OH,F)_2$
arfvedsonite	$Na_3(Fe^{2+},Mg)_4Fe^{3+}Si_8O_{22}(OH)_2$
astrophyllite	$(K,Na)_3(Fe^{2+},Mn)_7Ti_2Si_8O_{24}(O,OH)_7$
bertrandite	$Be_4Si_2O_7(OH)_2$
biotite	$K(Mg,Fe^{2+})_3(Al,Fe^{3+})Si_3O_{10}(OH,F)_2$
britholite-(Ce)	$(Ce,Ca)_5(SiO_4,PO_4)_3(OH,F)$
britholite-(La)	$(La,Ca)_5(SiO_4,PO_4)_3(OH,F)$
Ca-catapleiite	$CaZrSi_3O92H_2O$
chamosite	$(Fe^{2+},Mg,Fe^{3+})_5Al(Si_3Al)O_{10}(OH,O)_8$
clinochlore	$(Mg,Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$
danalite	$Fe_4^{2+}Be_3(SiO_4)_3S$
fayalite	$Fe_2^{2+}SiO_4$
ferrobustamite	$Ca(Fe^{2+},Ca,Mn)Si_2O_6$
ferrorichterite	$Na_2Ca(Fe^{2+},Mg)_5Si_8O_{22}(OH)_2$
gadolinite-(Y)	$Y_2Fe^{2+}Be_2Si_2O_{10}$
helvite	$Mn_4Be_3(SiO_4)_3S$
lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$
mesolite(?)	$Na_2Ca_2Al_6Si_9O_{30}:8H_2O$
microcline	$KAlSi_3O_8$
muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$
natrolite	$Na_2Al_2Si_3O_{10}:2H_2O$
nepheline	$NaAlSiO_4$
orthoclase	$KAlSi_3O_8$
pectolite	$NaCa_2Si_3O_8(OH)$
phenakite	Be_2SiO_4
polylithionite	$KLi_2AlSi_4O_{10}(F,OH)_2$
quartz	SiO_2
riebeckite	$Na_2(Fe^{2+},Mg)_3Fe_2^{3+}Si_8O_{22}(OH)_2$
sodalite	$Na_8Al_6Si_6O_{24}Cl_2$
thorite	$ThSiO_4$
topaz	$Al_2SiO_4(F,OH)_2$
willemite	Zn_2SiO_4
wollastonite	$CaSiO_3$
zinnwaldite	$KLiFe^{2+}Al(AlSi_3)O_{10}(F,OH)_2$
zircon	$ZrSiO_4$
Unidentified minerals	hydrated Fe silicate
	Ca,Nb,Ti silicate
	Ca,Nb silicate
	Th,Fe Silicate
	Nb,U,Ti silicate

TABLE 1 CONT.

OXIDES

NAME	FORMULA
aeschynite-(Nd)	$(Nd,Ce,Ca)(Ti,Nb)_2(O,OH)_6$
anatase	TiO_2
ashanite(?)	$(Nb,Ta,U,Fe,Mn)_4O_8$
betafite	$(Ca,Na,U)_2(Ti,Nb)_2O_6(OH)$
cassiterite	SnO_2
cerianite-(Ce)	$(Ce^{4+},Th)O_2$
ceriopyrochlore-(Ce)	$(Ce,Ca,Y)_2(Nb,Ta)_2O_6(OH,F)$
fergusonite-(Y)	$YNbO_4$
ferrocolumbite	$Fe^{2+}Nb_2O_6$
fersmite(?)	$(Ca,Ce)(Nb,Ta,Ti)_2(O,OH,F)_6$
goethite	$Fe^{3+}O(OH)$
hematite	Fe_2O_3
hydrohetaerolite	$Zn_2Mn_4^{3+}O_8:H_2O$
ilmenite	$Fe^{2+}TiO_3$
ixiolite	$(Ta,Nb,Sn,Fe,Mn)_4O_8$
magnetite	$Fe^{2+}Fe_2^{3+}O_4$
nioboaeschynite-(Ce)	$(Ce,Nd)(Nb,Ti)_2(O,OH)_6$
nioboaeschynite-(Nd)	$(Nd,Ce)(Nb,Ti)_2(O,OH)_6$
pyrochlore	$(Ca,Na)_2Nb_2O_6(OH,F)$
rutile	TiO_2
samarskite-(Y)(?)	$(Y,Fe,U,Ce)(Nb,Ta,Ti)O_4$
uraninite(?)	UO_2
uranpyrochlore	$(U,Ca,Ce)_2(Nb,Ta)_2O_6(OH,F)$

SULPHIDES

NAME	FORMULA
arsenopyrite	FeAsS
chalcopyrite	$CuFeS_2$
galena	PbS
gersdorffite(?)	NiAsS
marcasite	FeS_2
molybdenite	MoS_2
pyrite	FeS_2
pyrrhotite	$Fe_{1-x}S$, x=0-0.17
sphalerite	(Zn,Fe)S

FLUORIDES

NAME	FORMULA
fluorite	CaF_2

TABLE 1 CONT.

CARBONATES

NAME	FORMULA
ankerite	$Ca(Fe^{2+},Mn)(CO_3)_2$
bastnäsite	$(Ce,La)(CO_3)F$
calcite	$CaCO_3$
dolomite	$CaMg(CO_3)_2$
malachite(?)	$Cu_2(CO_3)(OH)_2$
parisite-(Ce)	$Ca(Ce,La)_2(CO_3)_3F_2$
rhodochrosite	$MnCO_3$
röntgenite-(Ce)	$Ca_2(Ce,La)_3(CO_3)_5F_3$
siderite	$Fe^{2+}CO_3$
synchysite	$Ca(Ce,La)(CO_3)_2F$

PHOSPHATES

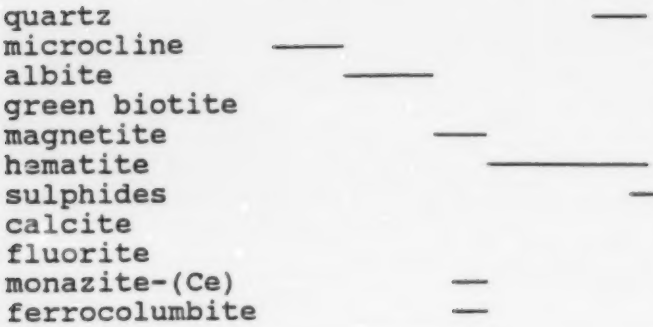
NAME	FORMULA
fluorapatite	$Ca_5(PO_4)_3F$
monazite-(Ce)	$(Ce,La,Nd,Th)PO_4$
xenotime-(Y)	YPO_4

* All formulae based on Fleischer (1987)

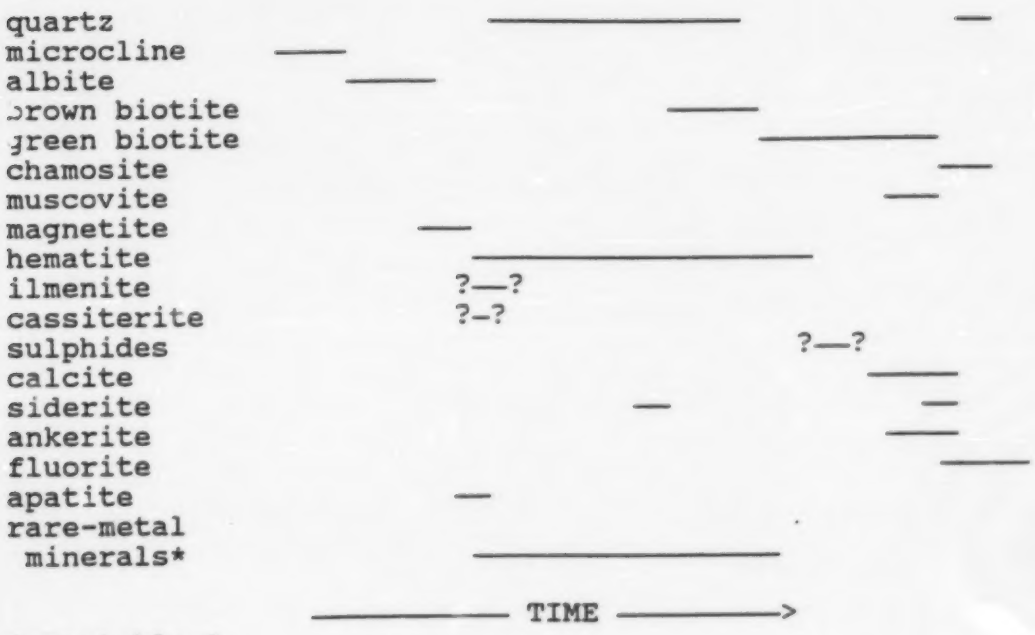
TABLE 2

PARAGENESIS OF THE ROCK-FORMING AND ACCESSORY MINERALS IN THE WALL AND CORE ZONES

WALL ZONE



CORE ZONE



*see table 3

TABLE 3
PARAGENESIS OF THE RARE METAL-BEARING MINERALS

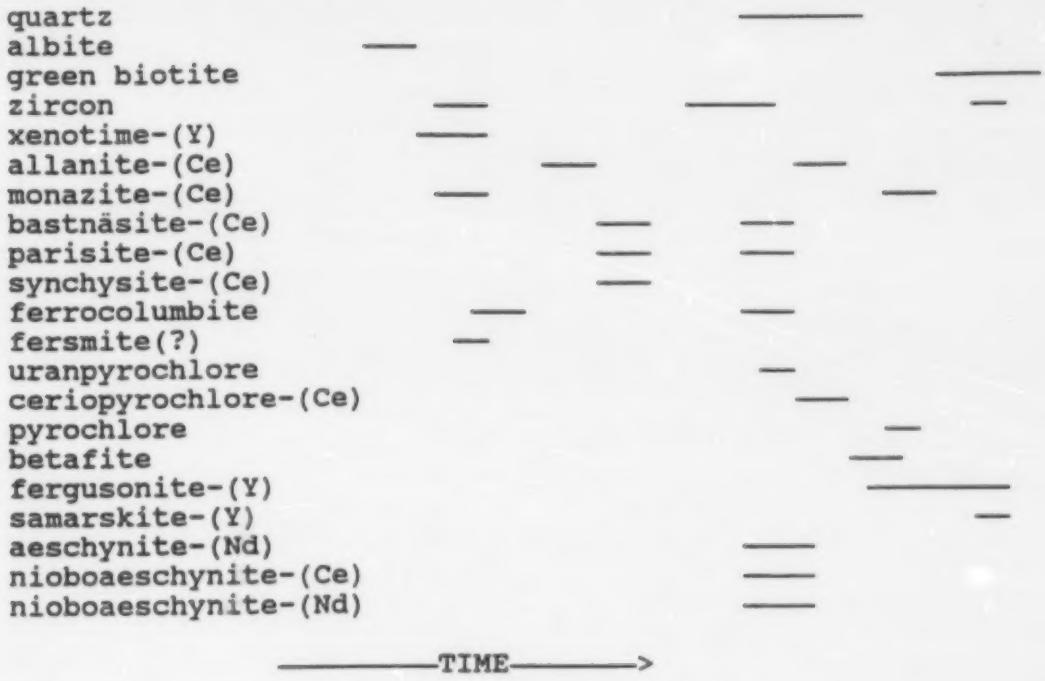


TABLE 4

Lake Zone Mineral Microprobe Analyses

	ZIRCON	FERRO-COLUMBITE	PYRO-CHLORE	BETA-FITE	CERIO-PYROCHLORE	URAN-PYROCHLORE	FERGUSONITE-Y	-MN-ALLANITE	MONAZITE
	PT5	ANAL.125	PT13	PT16	PT18	PT40	PT2	PT16	PT1
Na_2O	n.d.	n.d.	0.31	0.47	n.d.	0.25	0.09	0.07	-
MgO	n.d.	0.33	n.d.	0.88	n.d.	n.d.	n.d.	n.d.	-
Al_2O_3	0.15	0.12	0.08	0.22	0.26	0.25	0.06	17.27	-
SiO_2	26.27	0.12	4.7	1.62	2.85	1.82	0.06	31.02	-
P_2O_5	0.13	-	-	-	-	-	-	n.d.	29.4
CaO	0.14	n.d.	3.76	5.13	2.77	2.27	0.22	11.76	0.06
TiO_2	n.d.	3.57	5.6	17.87	9.21	2.39	n.d.	n.d.	-
Sc_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	-	-	-
MnO	n.d.	2.61	0.45	0.18	0.15	0.39	n.d.	8.17	-
FeO	0.86	12.2	4.88	8.71	1.65	4.53	n.d.	n.d.	-
Fe_2O_3	-	8.31	-	-	-	-	-	5.12	-
ZnO	n.d.	-	-	-	-	-	-	1.26	-
Y_2O_3	1.95	n.d.	n.d.	n.d.	n.d.	n.d.	13.89	n.d.	-
ZrO_2	54.17	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	-
HfO_2	1.02	-	-	-	-	-	-	-	-
La_2O_3	n.d.	-	0.47	n.d.	1.06	0.7	0.18	5.02	13.88
Ce_2O_3	n.d.	-	3.09	0.73	8.97	3.24	2.21	12.27	38.51
Pr_2O_3	n.d.	-	0.24	n.d.	0.74	0.38	0.86	0.85	3.05
Nd_2O_3	n.d.	-	0.7	n.d.	2.93	1.57	8.43	3.71	12.65
Sm_2O_3	0.21	-	n.d.	n.d.	0.50	0.35	5.8	0.4	1.16
Eu_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	0.94	-	-
Gd_2O_3	0.52	-	n.d.	n.d.	n.d.	n.d.	7.1	n.d.	-
Tb_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	0.66	-	-
Dy_2O_3	0.73	-	n.d.	n.d.	n.d.	n.d.	3.52	-	-
Ho_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	0.23	-	-
Er_2O_3	0.23	-	n.d.	n.d.	n.d.	n.d.	1.99	-	-
Tm_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	0.59	-	-
Yb_2O_3	n.d.	-	n.d.	n.d.	n.d.	n.d.	4.72	-	-
Lu_2O_3	-	-	n.d.	n.d.	n.d.	n.d.	0.65	-	-
ThO_2	n.d.	-	1.39	n.d.	n.d.	n.d.	0.35	n.d.	-
UO_2	n.d.	0.46	6.35	2.82	8.85	29.06	n.d.	n.d.	-
PbO	n.d.	-	n.d.	n.d.	0.81	2.6	n.d.	n.d.	-
Nb_2O_5	2.71	70.64	52.54	52.83	46.55	42.69	45.01	-	-
Ta_2O_5	0.18	1.01	1.62	0.35	0.37	0.48	1.4	-	-
SnO_2	-	-	n.d.	n.d.	0.27	0.19	-	-	-
WO_3	-	-	n.d.	n.d.	0.16	n.d.	0.11	-	-
H_2O^*	-	-	10.74	7.39	10.33	5.98	-	1.57	-
F	0.34	-	n.d.	n.d	n.d	n.d	0.19	-	0.38
O=F	-0.14		-	-	-	-	-0.08	-	-0.16
Total	89.47	99.37	96.92	99.20	98.43	99.14	99.18	98.49	98.93

*H_2O values by calculation

n.d. = not detectable

- = not sought